Twists to Solar Spicules

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Abstract.   Type-II solar spicules appear as long, thin, highly dynamic strands of field-tied matter that feed significant mass and energy to the corona and solar wind. A recent result is that they exhibit torsional Alfvén waves in addition to accelerating outflows and swaying motions due to transverse Alfvénic waves. I summarize this finding and then re-interpret older observations in its light: the striking similarity of near-limb scenes in the outer blue and red wings of Hα, and the tilts of absorption lines with respect to emission lines in eclipse spectra taken in 1973.

1.   Utrecht solar physics

I spent 50 years in Utrecht astronomy, arriving as a student in the autumn of 1961 and cleaning out my desk at the near-defunct Sterrekundig Instituut Utrecht (SIU) in the autumn of 2011[1]. Mostly in solar physics, making me expect an invitation to review Utrecht solar physics for you. When it didn't come I offered this contributed talk on recent results, but I place these here in earlier Utrecht context. And let me summarily add that in the hands of Minnaert, de Jager and Zwaan with their pupils Utrecht solar physics was a major player in the field. Utrecht (meaning Dutch) solar physics is now dead, but its legacy lives on abroad[2].

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[1] My last act at the SIU was to scan the lecture notes and practicals (in Dutch) of M.G.J. Minnaert who in 1961–1963 gave his wide-ranging undergraduate courses (one year planets, one year stars) for the last time. I posted them on my website (Google "Rob Rutten"). There I also describe the SIU closure and list the nearly 60 Utrecht solar physics PhDs.

[2] Utrecht University alumni employed elsewhere who are active in solar physics and collectively embody the great name that Utrecht University had in this field but discarded, in PhD order: Henk Spruit (München, Germany), Aad van Ballegooijen (Cambridge, USA), Piet Martens (Bozeman, USA), Karel Schrijver (Palo Alto, USA), Paul Hick (San Diego, USA), Han Uitenbroek (Sunspot, USA), Jo Bruls (Freiburg, Germany), Martin Volwerk (Graz, Austria), Kostas Tziotziou (Athens, Greece), Luc Rouppe van der Voort (Oslo, Norway), Michiel van Noort (Lindau, Germany), Alfred de Wijn (Boulder, USA), Jorrit Leenaarts (Oslo, Norway), Nikola Vitas (La Laguna, Spain), Catherine Fischer (Noordwijk, ESA), Gregal Vissers (Oslo, Norway), Tijmen van Wettum (Freiburg, Germany). Plus active-pensioner alumni Kees de Jager (Texel, The Netherlands), Jacques Beckers (Scottsdale, USA), myself.

2.   Chromosphere research at Utrecht and elsewhere

Soon after I started at Utrecht Beckers defended his famous thesis on the fine structure of the chromosphere (Beckers 1964)[3]. At Utrecht the efforts in chromosphere research at that time consisted of Houtgast's eclipse expeditions to collect high-dispersion flash spectrum photography and "Utrecht reference model" building by De Jager with Heintze and Hubenet. Houtgast took me along to Greece and Brazil in 1966, to Mexico in 1970; I wrote my thesis on partial redistribution in line formation on data from the third expedition, with Zwaan as supervisor (I am proud that I was his first) and on the same topic as Houtgast's own famous thesis (Houtgast 1942). By then the basics of chromospheric NLTE-PRD line formation were well established, a landmark of early computational astrophysics masterly canonized in Mihalas (1970, 1978). Stuff I still teach with pleasure.

During the following three decades not much happened in chromosphere physics worldwide. In retrospect the field was on hold until computers matured. The chromosphere is the most difficult solar regime, far beyond snapshot observation and analytic modeling; it needs fast computation. In groundbased observing to permit real-time adaptive optics and large-volume post-detection wavefront restoration, in space-based observing to cope with high-cadence image streams, and in modeling to permit 3D(t) MHD simulations with realistic radiative transfer. Data dissection and visualization are major issues in each endeavor. Eventually they all advanced enough to turn the chromosphere from a non-doable topic into a hot topic. See Rutten (2012) for the latest review[4].

Utrecht solar physics became part of this chromosphere revival when Hammerschlag's Dutch Open Telescope (DOT, `http://www.dot.iac.es`) started taking Hα movies. Utrecht left it in September 2011 when Leenaarts took his Veni grant on Hα simulation to Oslo (the best leave first).

3.   New twist to spicules

Dynamic fibrils / spicules-I and straws / spicules-II / RBEs.   Still at the Sacramento Peak Observatory, Beckers wrote two authoritative reviews on solar spicules (Beckers 1968, 1972), a topic that thereafter suffered from utter lack of progress until dynamic fibrils were identified and explained by Hansteen et al. (2006) and De Pontieu et al. (2007a). These are slanted-field wave guides in which p-mode-driven magneto-acoustic shock waves push matter up repetitively. Just off the limb they make up the dense forest of what we now call type-I spicules.

Type-II spicules extend much further up, as very thin, very dynamic strands. They were first glimpsed by me as long thin "straws" in near-limb Ca II H movies from the DOT (Rutten 2006), then observed in off-limb Ca II H movies from Hinode by De Pontieu et al. (2007b), and subsequently identified on the disk as blue-wing absorption

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[3] A Utrecht thesis with Minnaert as supervisor, but Beckers had done the work in Australia and moved to the Sacramento Peak Observatory. Recently he scanned the full text; I put it on ADS. Regrettably, the other Utrecht theses have not been scanned so far.

[4] Since then there is significant progress in our understanding of the formation of Hα, the quintessential chromosphere diagnostic (Rutten & Uitenbroek 2012; Leenaarts et al. 2012). I don't have space here to explain it but do in my (Google for it) "Graphical introduction to NLTE chromospheric line formation".

features in Hα (Rapid Blue Excursions, RBEs) by Rouppe van der Voort et al. (2009). De Pontieu et al. (2007c) identified their large off-limb swaying as upward propagating transverse Alfvénic waves. They are now thought to be important contributors to coronal heating and mass loading (De Pontieu et al. 2009), shooting blobs of matter up as bullets that are also diagnosed in extreme-ultraviolet imaging (De Pontieu et al. 2011) and spectroscopy (Tian et al. 2011).

Torsion waves next to outflows and swaying.   A new aspect, namely twist, of type-II spicules emerged during the past year. This finding is being published elsewhere (De Pontieu et al. 2012). It was inspired by old near-limb DOT Hα-sampling observations that in the far wings showed only upright fibrils, rooted in network, much like straws and off-limb type-II spicules, whereas at line center a dense carpet of long horizontally spread-out fibrils covering cell interiors is seen (Fig. 7 of Rutten 2007; Fig. 1 here).

This outer-wing scene is remarkably similar in the blue and red wings. At the time this similarity was puzzling because spicules were then thought to be slanted extending and retracting jets. If the corresponding Dopplershifts would define their outer-wing appearance one would expect larger Dopplershift plus spatial foreshortening for spicules slanted towards the observer. A.G. de Wijn then suggested that the similarity might come from huge thermal broadening which would produce identical outer-wing appearance, but we couldn't verify this idea because the DOT speckle-burst profile sampling took too long to compare red and blue outer-wing scenes sufficiently fast.

Our new analysis uses much higher-cadence spectral sampling with the Swedish 1-m Solar Telescope (SST). These data show that the outer-wing scenes have indeed large similarity but are not identical. Often the similarity between the two wings improves when comparing them at a brief time delay. B. De Pontieu then suggested that the similarity results from twisting motions with rapid sign changes giving transverse Dopplershifts. Such spicule twists were earlier suggested by Suematsu et al. (2008) but without Doppler discrimination. The clincher SST observation was that these motions produce tilted spicular Dopplershift signature in off-limb Ca II H spectra and near-limb Ca II 854.2 nm imaging spectroscopy. The tilts change fast. A Monte Carlo simulation served to establish that their complex time-dependent spectral and spatial behavior results from combining outward accelerating upflows with both transverse and torsional Alfvén waves that also propagate upwards, with much phase and periodicity mixing. See De Pontieu et al. (2012) for more detail.

4.   Old twist to spicules

DOT near-limb Hα.   While preparing this presentation I realized, belatedly, that the old DOT observations might still serve to illustrate these various type-II spicule motions by constructing time-delay Dopplergrams $[I_b(0) - I_r(\Delta t)] / [I_b(0) + I_r(\Delta t)]$ from a blue-wing image I_b and a red-wing image I_r taken Δt later (Figs. 1 and 2).

The first row of Fig. 1 displays the photospheric scene and the overlying Hα line-center fibril carpet[5]. The second row illustrates the similarity but non-identity of blue and red outer-wing images at $\Delta\lambda = \pm 800$ mÅ. One sees the same bushes but made up of different spicular features. The third panel is a time-delay Dopplergram at $\Delta\lambda =$

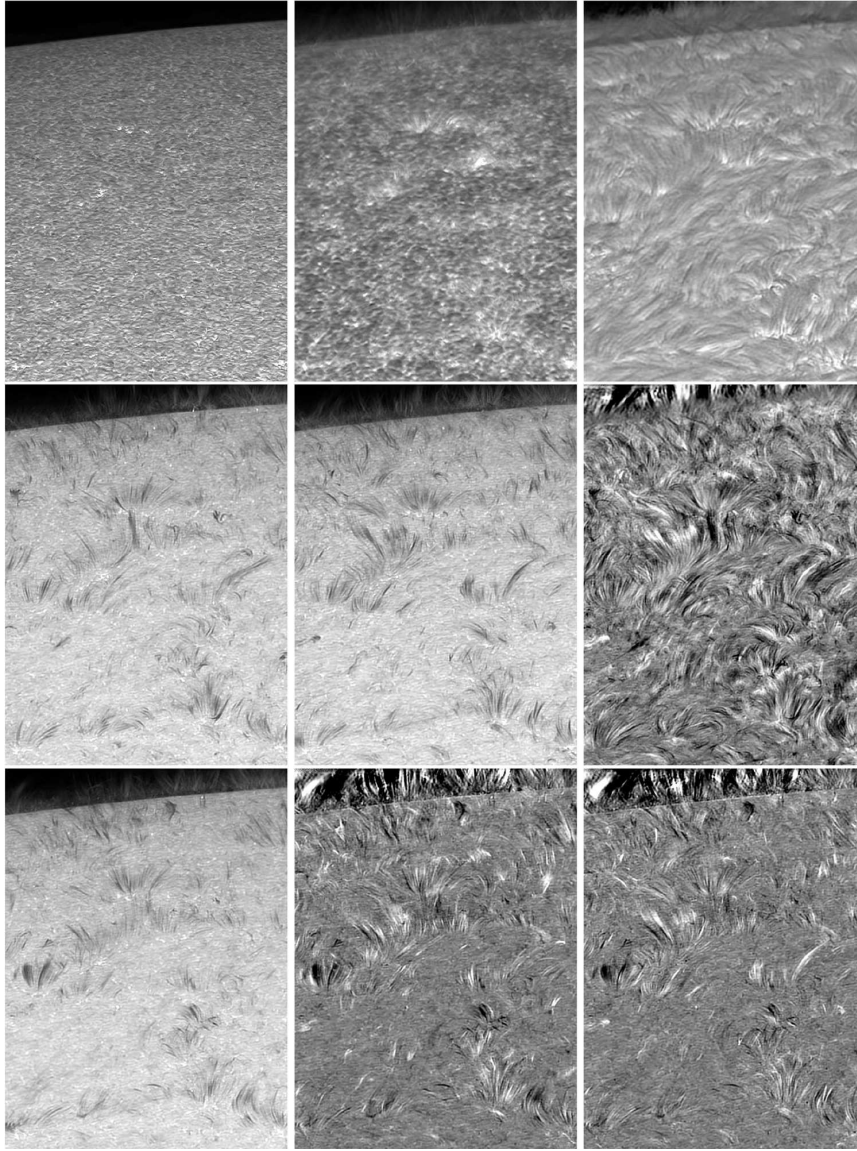[5] The sharp limb is probably parasitic continuum light (cf. Bray & Loughhead 1974).

Figure 1.   Near-limb DOT images taken on October 4, 2005 and available in the DOT database. I suggest to zoom in with a PDF viewer to appreciate their detail. Field of view $60'' \times 80''$. Top row: G-band image showing photospheric granulation and faculae, Ca II H image showing bright network with thin straws and diffuse emission, elsewhere dark cell interiors with bright acoustic-shock grains, Hα line center image showing masses of fibrils, most of them covering cell interiors. These three images were taken simultaneously. Middle row: $\Delta\lambda = -800$ mÅ and $+800$ mÅ images taken slightly earlier. These show only upright fibrils jutting out from network. They are similar but not identical. Third panel: ± 600 mÅ time-delay Dopplergram at $\Delta t = 1$ minute. Bottom row: -800 mÅ image taken four minutes earlier and ± 800 mÅ time-delay Dopplergrams at $\Delta t = 2$ and 4 minutes. Observation and alignment: P. Sütterlin.
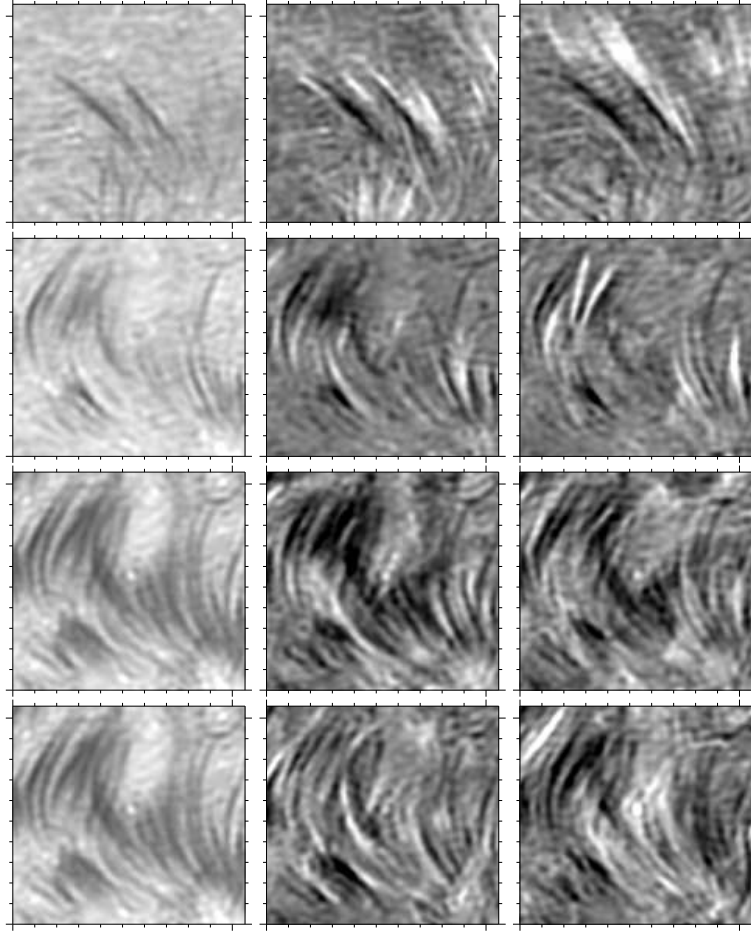
Figure 2.   First two rows: enlarged cutouts of the bottom panels in Fig. 1, for subfields at the upper-right from the center and in the lower-right corner. Third row: same subfield as in the second row, but using $\Delta\lambda = \pm 600$ mÅ images (taken at slightly different times from those in the second row). Bottom row: same subfield as in the second row, but the second and third panels are now same-wavelength time-delay difference images subtracting successive -600 mÅ images at about two and four minutes delay. The axis ticks are $1''$ apart.

± 600 mÅ and $\Delta t = 1$ minute. Bright features represent spicules in the red-wing image. The smaller wavelength separation is chosen because for extreme Dopplershift the line-of-sight components of outflow, to-from swaying, and torsional motion must add up constructively and this is unlikely to happen in both wings at nearly the same time. At his smaller Dopplershift there are many instances of aligned look-alike black and white features. Thus, parts of a given spicule bush may appear black or white, i.e., Dopplershifted into the blue or the red wing, without slant discrimination. The third row shows an earlier -800 mÅ image and time-delay Dopplergrams with it at two and four minutes delay. Juxtaposition of dark and subsequent bright features indicates opposite blueshift and redshift at these time intervals. At these longer delays these Dopplergrams

also show similar morphology of network spicule bushes in black and in white in many locations. Significant change occurs between the two delay samplings.

Figure 2 magnifies two subfields from the bottom row of Fig. 1 and adds 600 mÅ time-delay Dopplergrams and same-wavelength subtractions for the second subfield. Again the overall black-and-white Dopplergram similarity is striking. There are good examples of aligned black-and-white feature pairs in the Dopplergrams that indicate twist motion. In the top row the bright splash in the third panel extends out from the shorter feature seen earlier, indicating rising outflow away from the viewer. The pair of brightest streaks in the third panel of the second row are adjacent to similar but dark spicules in the blue-wing image, suggesting torsion plus sway Doppler reversal. The corresponding 600 mÅ Dopplergram underneath shows them only weakly, confirming that their redshifts are extreme.

Transverse spicule swaying observed as proper motion (movement in the plane of the sky) is better seen in higher-cadence movies as those of De Pontieu et al. (2007c), but it is also clear in the difference images in the bottom row of Fig. 2. Adjacent look-alike black and white features in these imply spicule swaying transverse to the line of sight. It is clearly evident in the first difference image, less in the second due to spicule evolution.

Overall, the morphology of the bright features in these various time-delay maps indeed suggests that many, if not most, spicules combine motions in these various modes. Clearly, high spatial resolution, fast cadence, and good spectral resolution as well as large spatial extent, long temporal duration, and multi-line spectral sampling are the way to nail their role. Also in simulations.

Last Utrecht eclipse expedition.   I then realized, yet more belatedly, that the tilt that the torsional wave mode gives to spectral lines at the limb explains the old riddle with which Houtgast and Namba concluded the Utrecht eclipse efforts long ago. At the 1973 eclipse they used a large grazing-incidence slitless échelle spectrometer with an image intensifier to take high-dispersion spectrograms in rapid cadence at second and third contact. The instrument and preparations are described in detail in Houtgast & Namba (1979a), the observations in Houtgast & Namba (1979b) – for each author the last research papers. The main result was that the absorption lines showed varying tilts with respect to the emission lines just before second contact. Figure 3 shows a sample. The tilts differ between the two Bailey beads and between different absorption lines. The maximum displacement was 0.08 Å, corresponding to 5 km s^{-1} if interpreted as Dopplershift which is more likely than slitless spatial mapping (corresponding to 30″ because the grazing incidence compressed the spatial dimension in the dispersion direction by a factor 3.4).

Houtgast and Namba were not sure that the tilts were not instrumental and indeed could produce line tilts in subsequent laboratory experiments with the spectrograph that came from the Dove prism used for image rotation, but this could not explain differential tilt between absorption and emission lines nor tilt variations. They concluded that the tilts remained without obvious explanation. I remember that Houtgast made a careful inventory of tilt per line type (element, atom/ion, strength, excitation energy) but I fear that his work is lost.

The answer appears simple now. The emission lines are rare earth lines which derive their emission from strong scattering with much interlocking, as shown by Canfield (1971) while he was a postdoc at Utrecht. These lines do not show local conditions but smoothed-out photospheric radiation from a wide area. Instead, the absorption lines
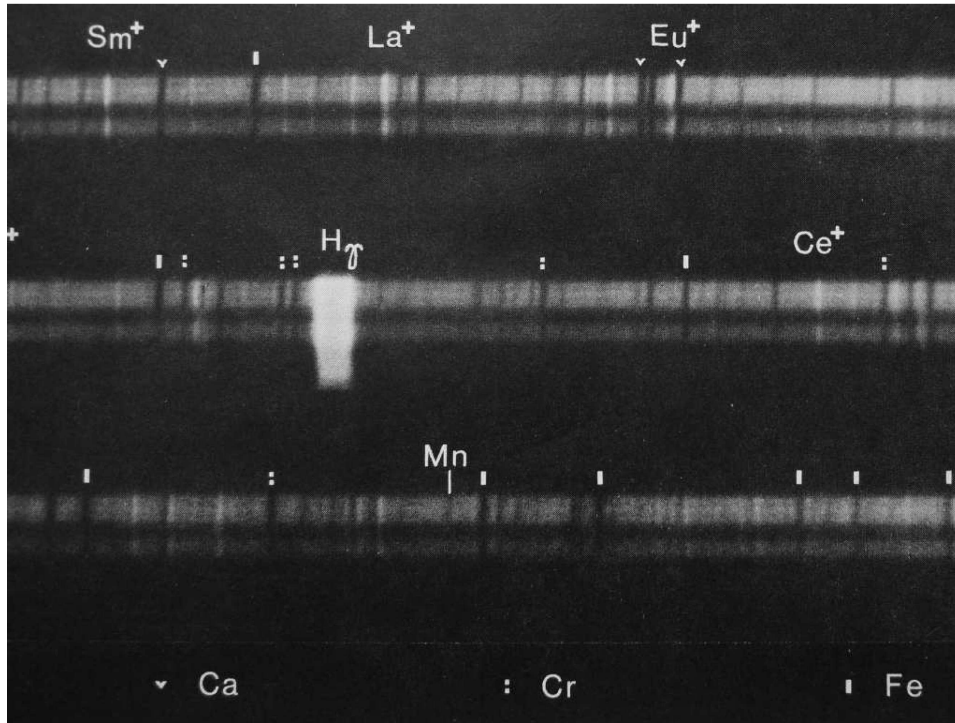
Figure 3.   Part of a spectrogram taken just before second contact of the June 30, 1973 eclipse at Atar, Mauritania. From Houtgast & Namba (1979b).

form close to LTE, respond to local conditions, and likely sampled a single spicule or spicule bush as selected by the Bailey bead (lunar limb valley), indeed with different formation and Doppler response for different lines. Their tilts then formed comparably to the near-limb line tilts in Fig. 5 of De Pontieu et al. (2012).

5.   Discussion

What are the next steps in spicule research? Observationally NASA's upcoming IRIS solar spectrometry mission (`http://iris.lmsal.com`) is slated to diagnose type-II spicules especially in Mg II h & k on the disk. In fast-scan imaging spectroscopy in these lines they are likely to appear as thin strands that are Dopplershifted well out of the central emission peaks to appear bright against the dark internetwork background, made extra dark through coherent inner-wing scattering. Their transverse torsional and swaying motions will contribute to this Doppler isolation.

In simulations the quest is to identify their acceleration and heating mechanisms. The fact that they occur in unipolar areas (McIntosh et al. 2011) suggests that component reconnection rather than opposite-polarity reconnection may be a major agent. The simulation example of Martínez-Sykora et al. (2011) indeed points this way.

I look forward in particular to limb spectroscopy with IRIS. More than forty years ago Houtgast taught me to appreciate the extreme limb in spectra. It will be good to return to it exploiting the extended seeing-free observing that space offers over eclipses.

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